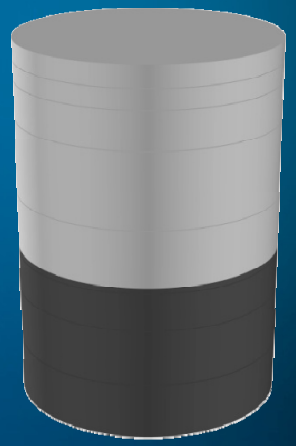
Benchmark Evaluation of Uranium Metal Annuli and Cylinders with Beryllium Reflectors

John Darrell Bess
R&D Staff Engineer
Reactor Physics Analysis & Design

June 15, 2010

ANS Annual Meeting



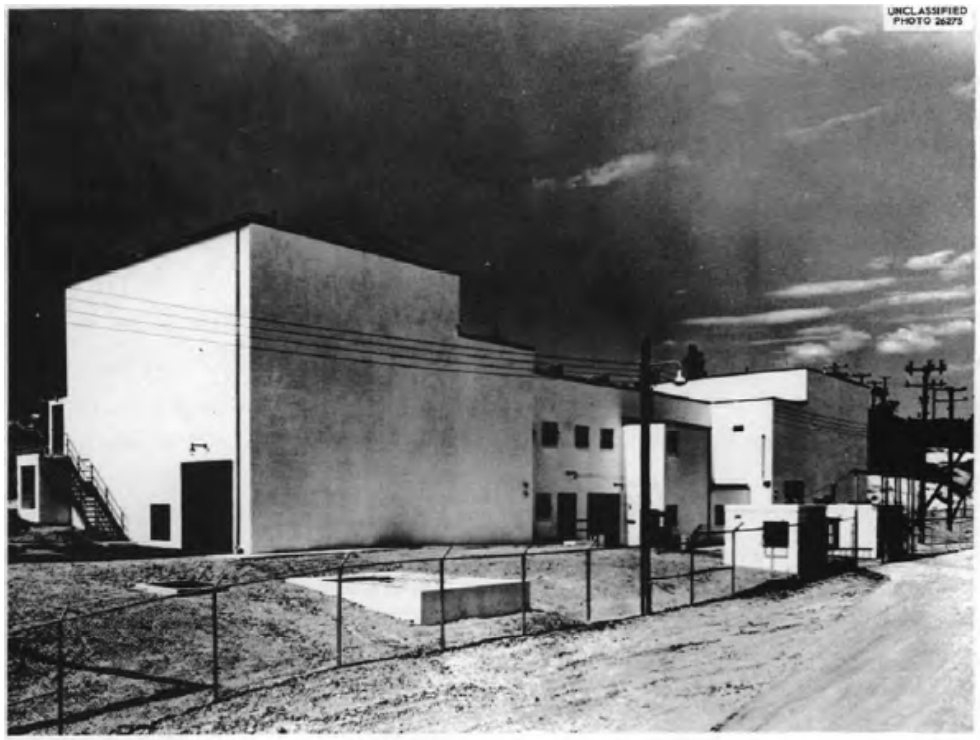
www.inl.gov

Idaho National Laboratory

This paper was prepared at Idaho National Laboratory for the U.S. Department of Energy under Contract Number (DE-AC07-05ID14517)

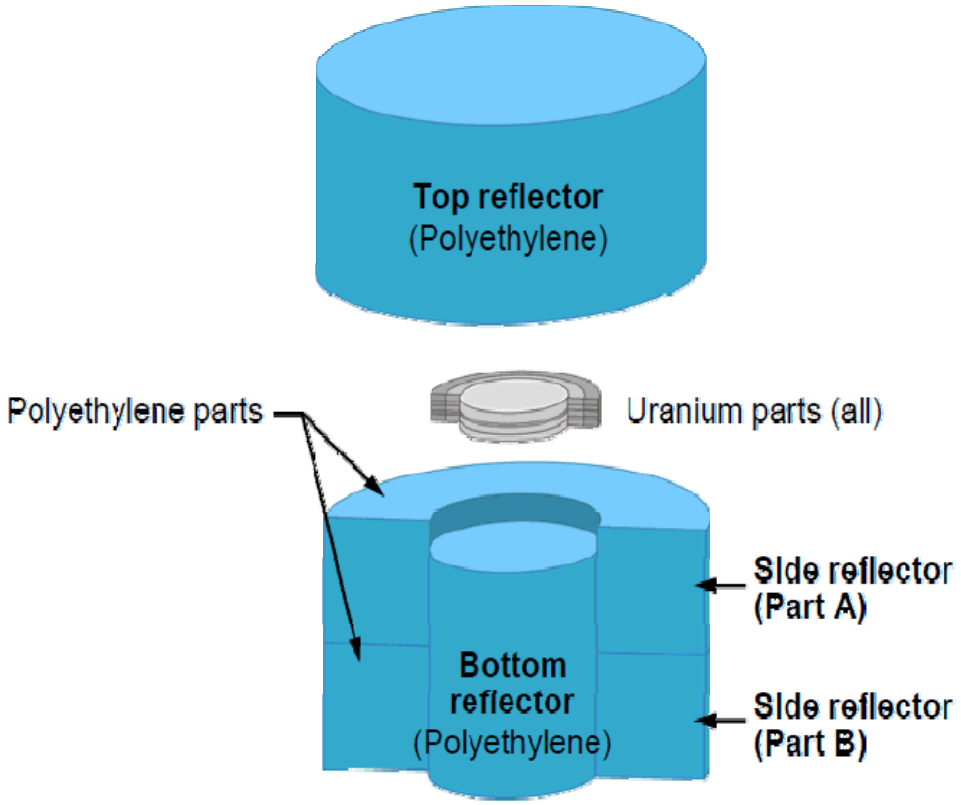
Background/History

- Oak Ridge Critical Experiments Facility (ORCEF)
  - Hundreds of HEU Oralloy Experiments
  - 1960s and 1970s
  - Support Criticality Safety at Y-12
    - Storage, Casting, and Handling
    - Verification of calculation methods and cross sections



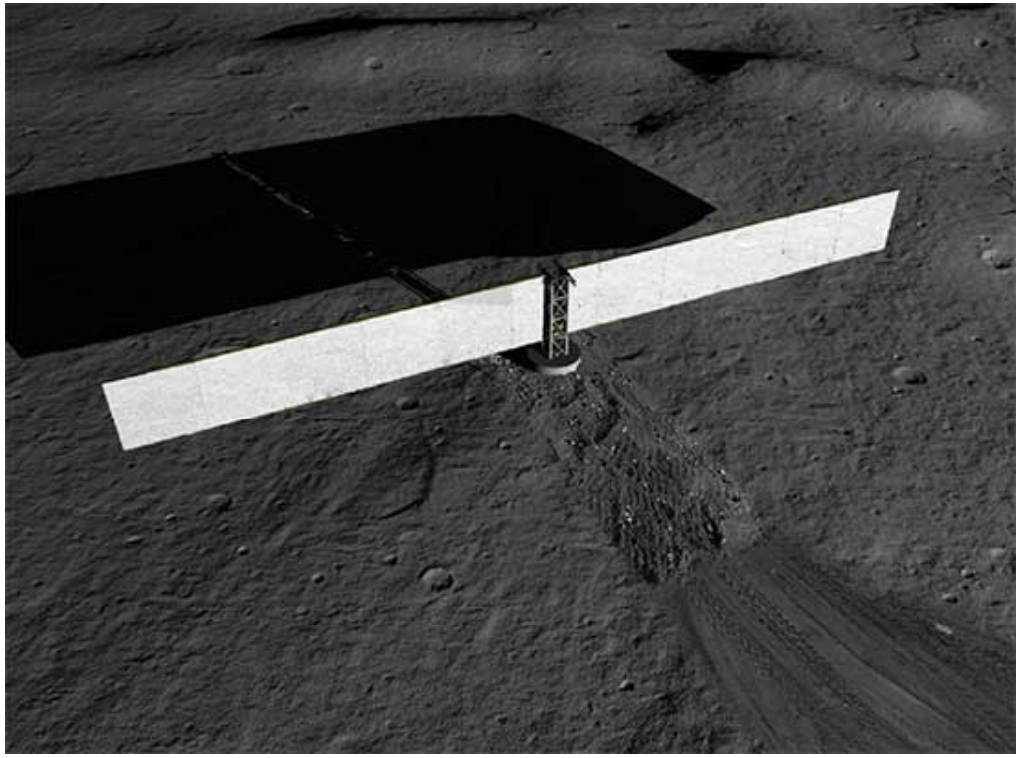
Oralloy Benchmark Experiments

- HEU-MET-FAST-051
  - Unreflected and unmoderated
- HEU-MET-FAST-071
  - Graphite reflected
- HEU-MET-FAST-076
  - Polyethylene reflected
- Three beryllium reflected experiments were performed

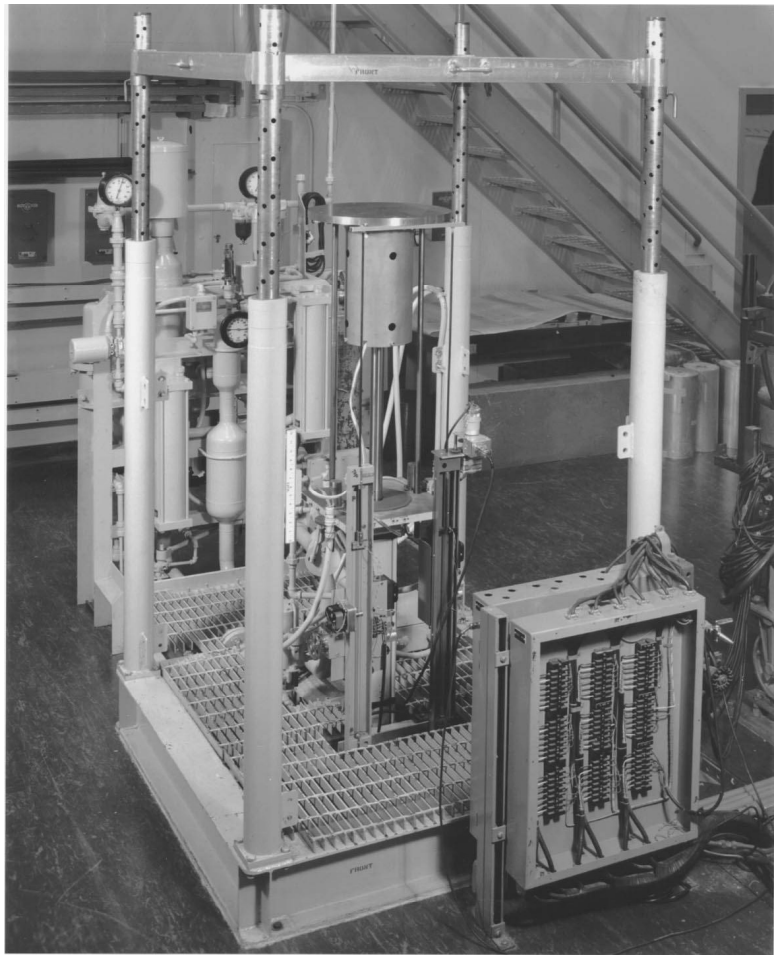


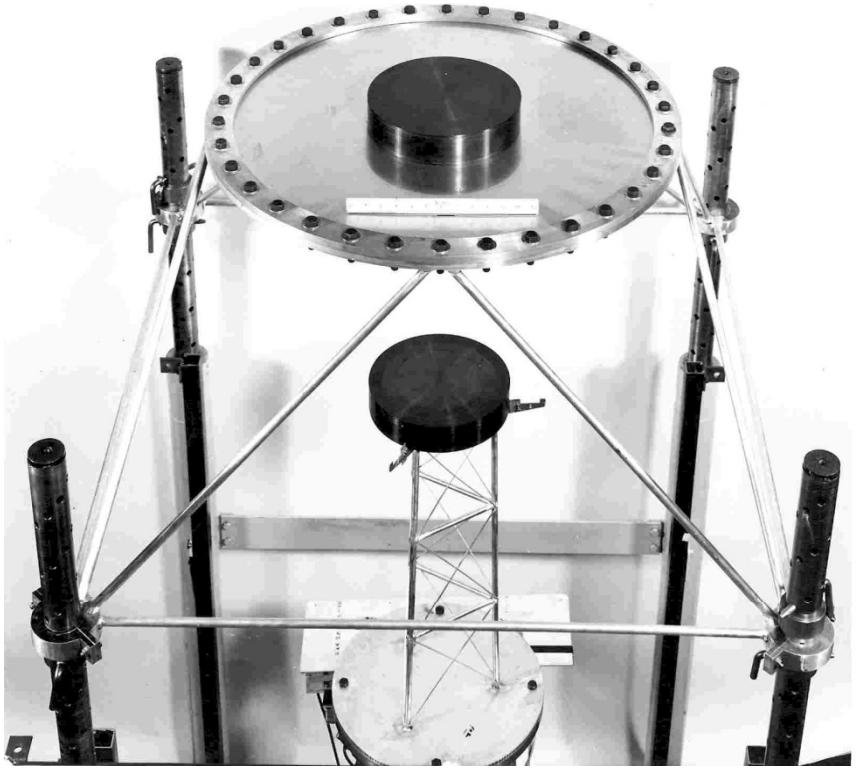
Why the Interest in Beryllium Reflection?

- Space nuclear reactors
  - HEU
  - Fast spectra
  - Compact size
  - Accident analyses
- Previous studies indicate design model uncertainties are dominated by Be(n,2n) reaction



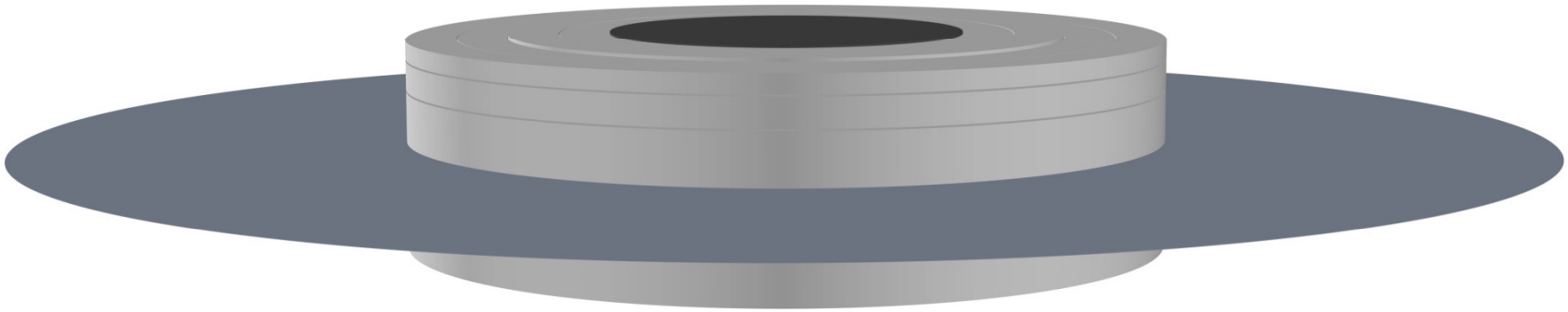
Vertical Lift Assembly





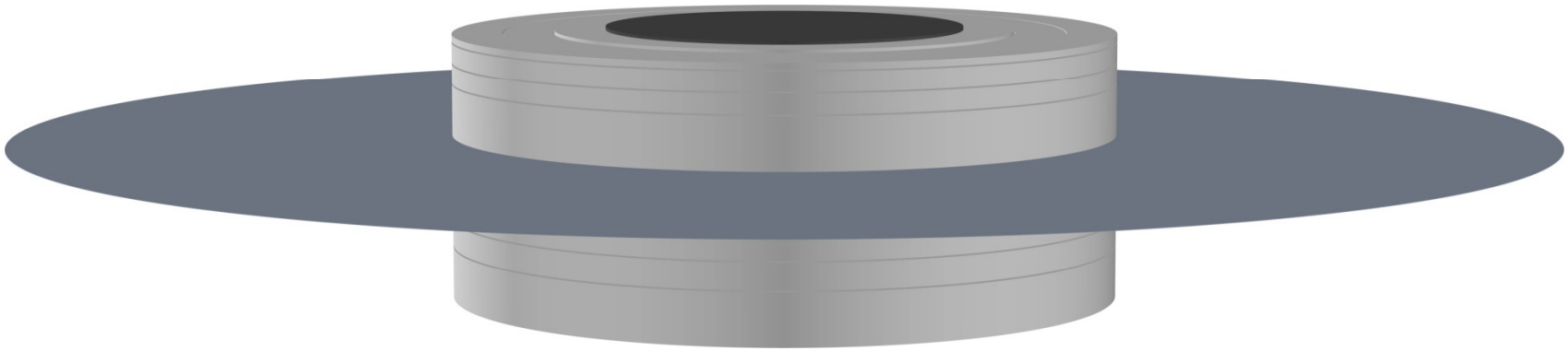
Annular Experiments: 15-inch Annulus

- June 4, 1963
- ~15 in. outer diameter
- ~7 in. diameter Be core
- ~4 in. high



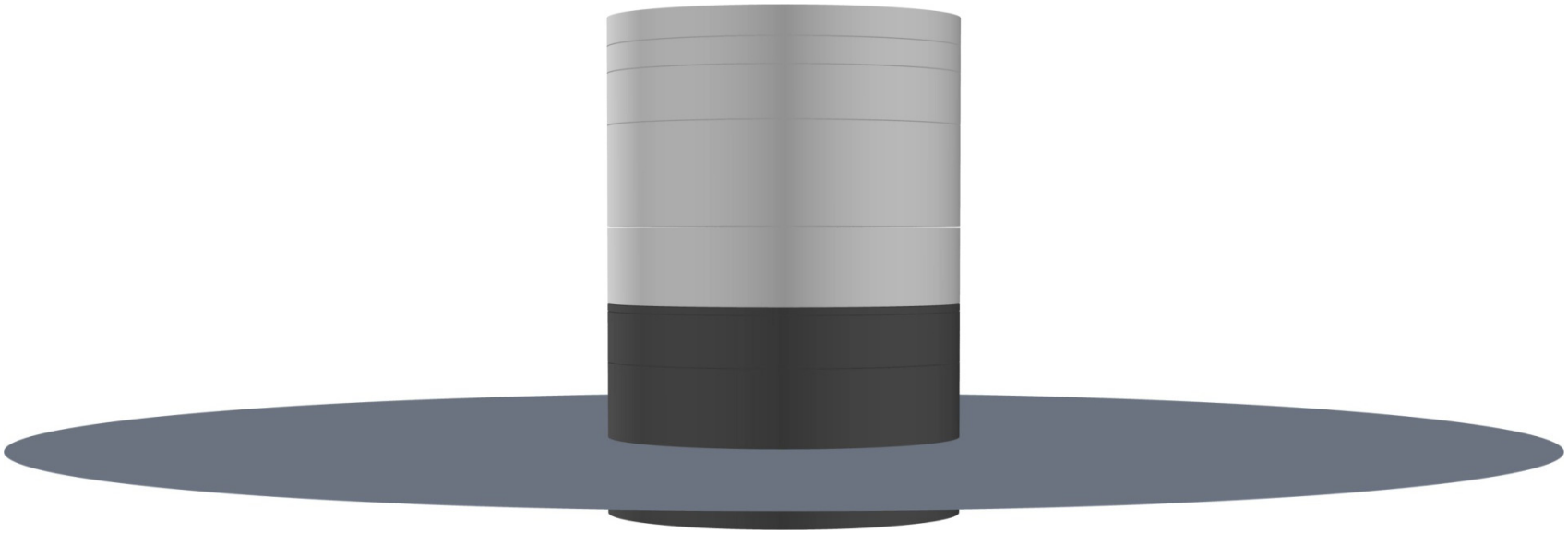
Annular Experiments: 13-inch Annulus

- July 12, 1963
- ~13 in. outer diameter
- ~7 in. diameter Be core
- ~5 in. high



Top-Reflected Experiment

- August 20, 1963
- ~7 in. diameter
- ~4-1/8 in. high HEU
- ~5-9/16 in. high Be



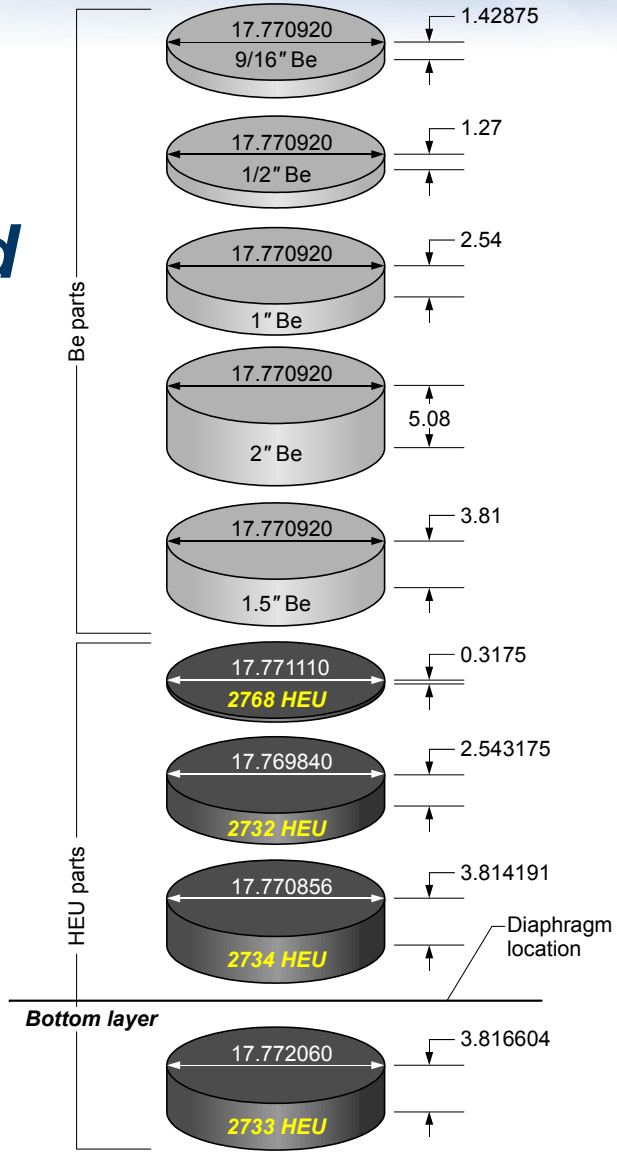
Evaluated Uncertainties

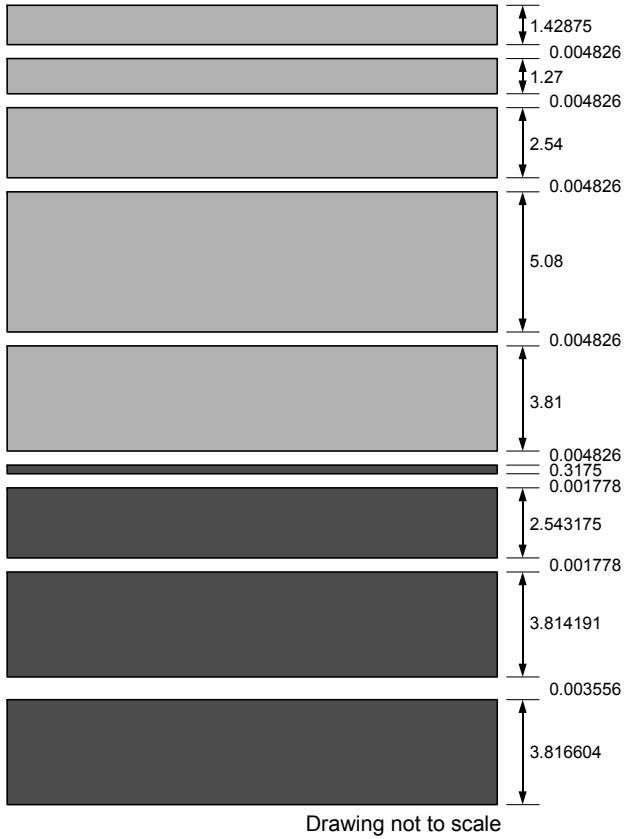
- Experimental
  - Temperature
  - Measurement of k_{eff}
  - Support Structure Worth
    - SS 304 Diaphragm
      - Includes gap
    - Rings
    - Low-Mass Support Stand
  - β_{eff}
  - Reproducibility
- Geometric
  - Diameter
  - Height
  - Stack Height
  - Assembly Alignment
- Composition
  - Mass
  - Isotopic Content
  - Impurities

Unique Uncertainty Conditions

- Parts manufactured at Y-12 measured with very small uncertainty
  - Dimensions:
    - ±0.0001 in.
  - Mass:
    - ±0.5 g
  - Isotopic Composition:
    - ±0.005 wt.%
  - Part Placement:
    - ±0.001 in.
- Now uncertainties that are typically insignificant become significant
  - Temperature:
    - ±2 ºF
  - Reactivity measurement:
    - ±10%
  - Beryllium impurities
    - Nominal quantities known but deviation unknown

Detailed Benchmark Model: Top-Reflected





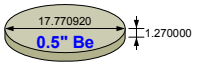
Drawing not to scale

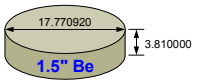
Dimensions in cm

09-GA50001-177-4

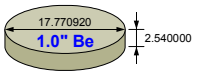
Detailed Benchmark Model: 13 in. Annulus

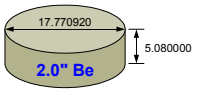
Top layer

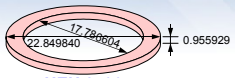




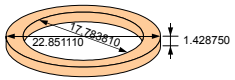
Bottom layer



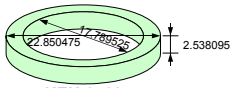




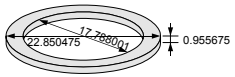
HEU 2736



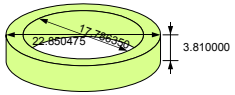
HEU 2737



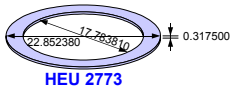
HEU 2762



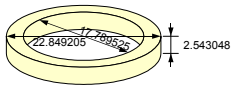
HEU 2829



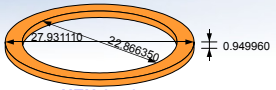
HEU 2740



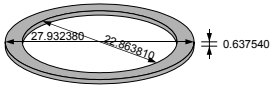
HEU 2773



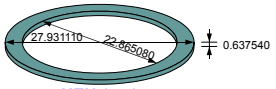
HEU 2738



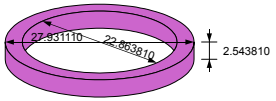
HEU 2743



HEU 2779

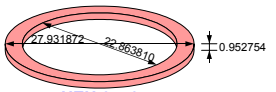


HEU 2778

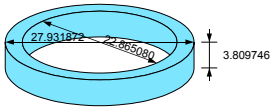


HEU 2776

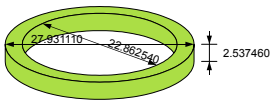
HEU 2744



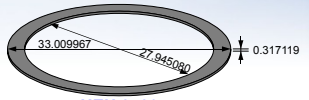
HEU 2742



HEU 2747



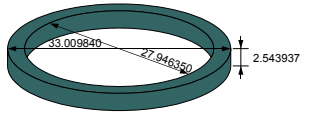
HEU 2745



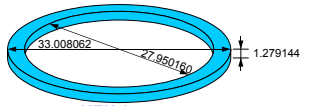
HEU 2780

HEU 2750

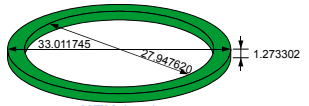
HEU 2749



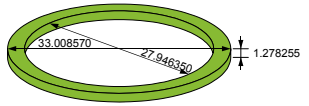
HEU 2757



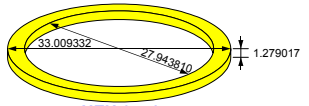
HEU 2754



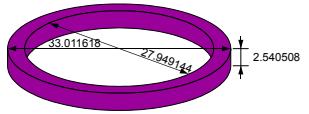
HEU 2753



HEU 2752



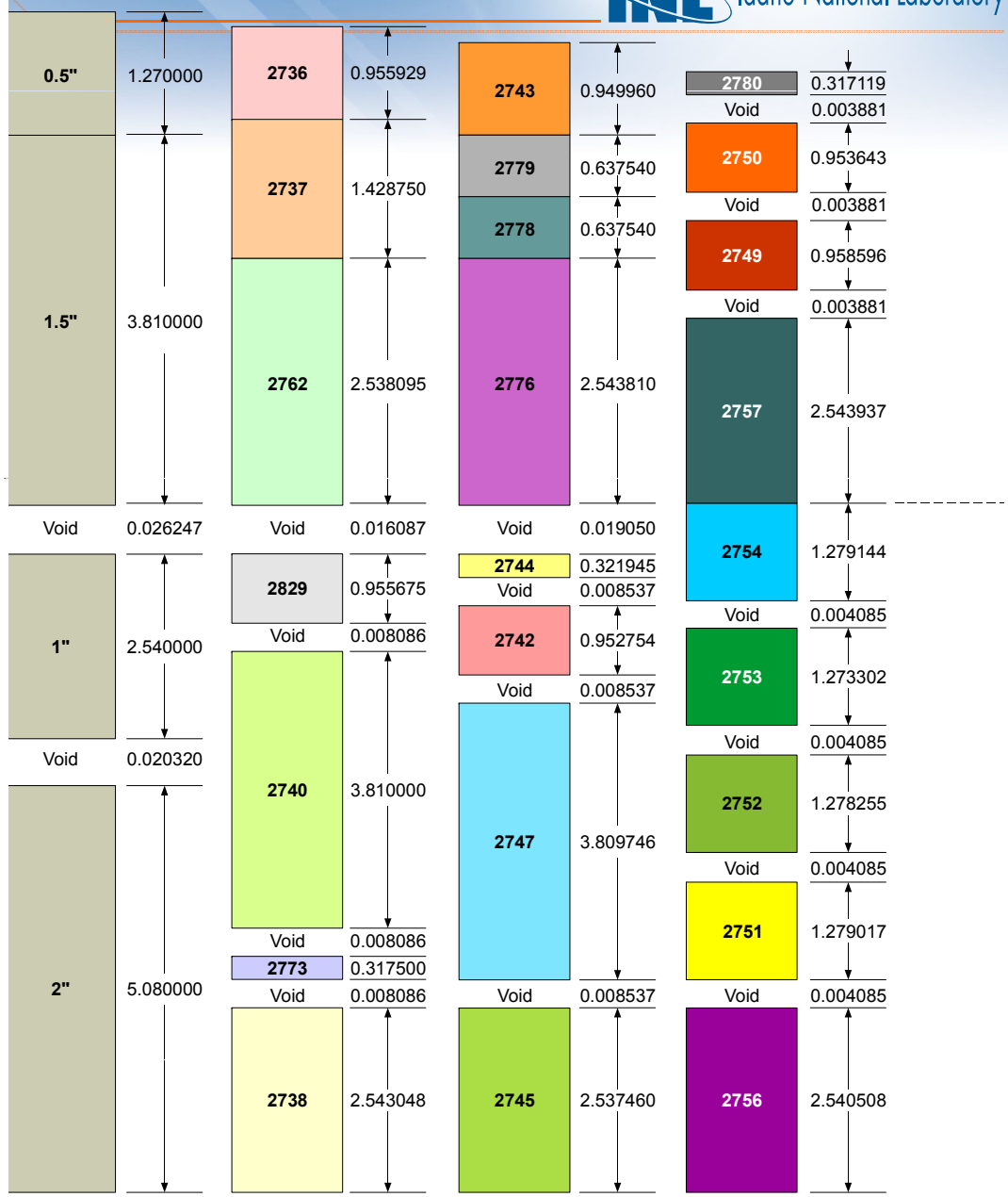
HEU 2751



HEU 2756

Dimensions in cm

Detailed Benchmark Model: 13 in. Annulus

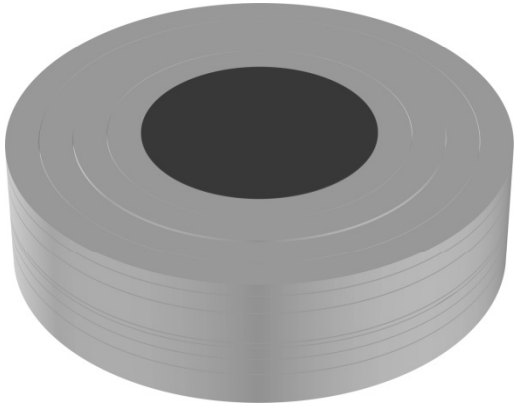


Drawing not to scale
Dimensions in cm

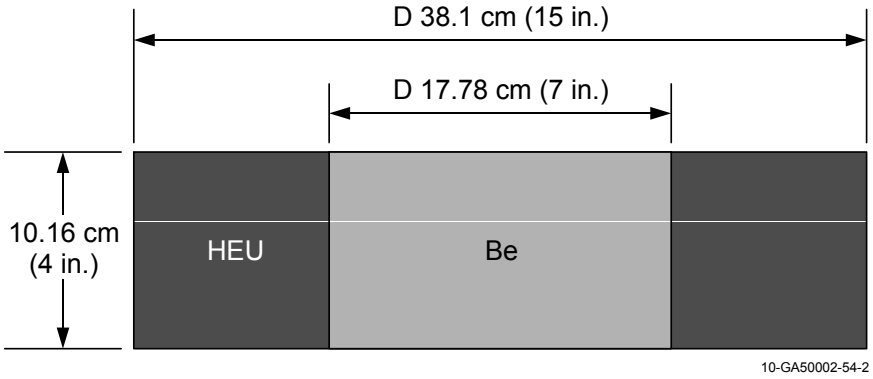
10-GA50002-53-8

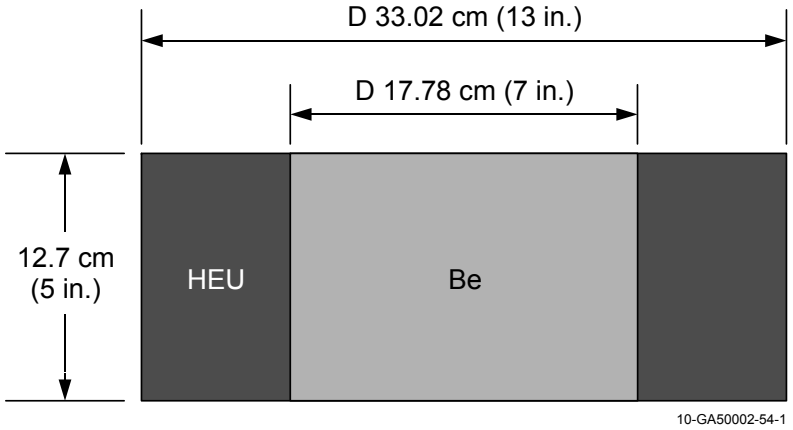
Evaluated Biases

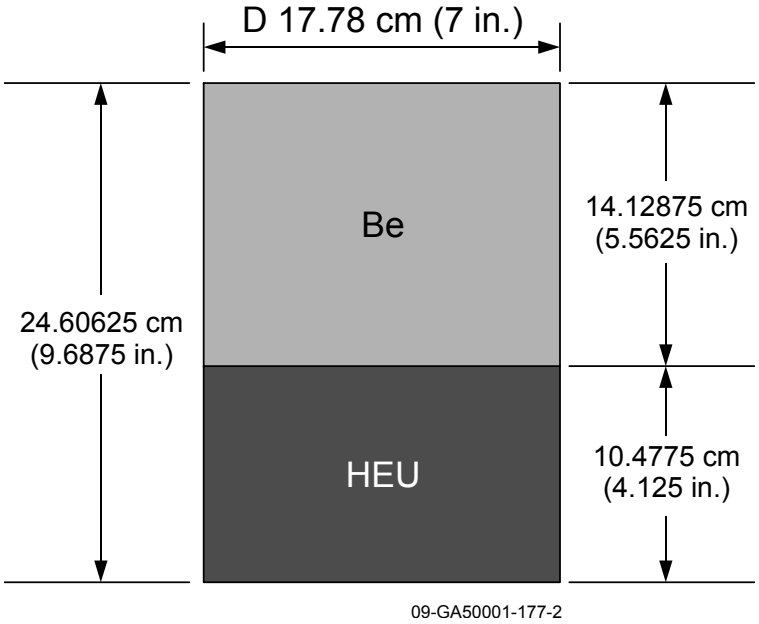
- Small biases are now significant due to small uncertainties
- Room return
- Removal of support structure
  - Measured/evaluated by experimenter
- Temperature
  - Treated as uncertainty
- Model Simplifications
  - Removal of impurities
  - Homogenization of like components
    - Removal of gaps
    - Uniform material properties
    - Nominal experiment dimensions



Simple Benchmark Models







Results: Top-Reflected Experiment

Detailed

Analysis Code	Neutron Cross Section Library	Calculated k_{eff} ± σ	Benchmark k_{eff} ± σ	$\frac{C-E}{E}(\%)$
MCNP5	ENDF/B-V.2	0.99614 ± 0.00004	0.9998 ± 0.0004	-0.37
	ENDF/B-VI.8	0.99619 ± 0.00004		-0.36
	ENDF/B-VII.0	0.99804 ± 0.00004		-0.18
	JEFF-3.1	0.99562 ± 0.00004		-0.42
	JENDL-3.3	1.00202 ± 0.00004		0.22
KENO-VI	ENDF/B-VII.0 (continuous energy)	0.99770 ± 0.00007		-0.21
	ENDF/B-VII.0 (238-group)	0.99754 ± 0.00005		-0.23

Simple

Analysis Code	Neutron Cross Section Library	Calculated k_{eff} ± σ	Benchmark k_{eff} ± σ	$\frac{C-E}{E}(\%)$
MCNP5	ENDF/B-V.2	0.99579 ± 0.00004	0.9995 ± 0.0004	-0.37
	ENDF/B-VI.8	0.99582 ± 0.00004		-0.37
	ENDF/B-VII.0	0.99781 ± 0.00004		-0.17
	JEFF-3.1	0.99531 ± 0.00004		-0.42
	JENDL-3.3	1.00166 ± 0.00004		0.22
KENO-V.a	ENDF/B-VII.0 (continuous energy)	0.99714 ± 0.00005		-0.24
	ENDF/B-VII.0 (238-group)	0.99726 ± 0.00005		-0.23

~0.64% Δk_{eff} between JEFF-3.1 and JENDL-3.3

Calculated values are ~4.4 to 10.5 σ from benchmark values

Results: 13 in. Annular Experiment

Detailed

Simple

Analysis Code	Neutron Cross Section Library	Calculated k_{eff} ± σ	Benchmark k_{eff} ± σ	$\frac{C-E}{E}(\%)$
MCNP5	ENDF/B-VII.0	0.99711 ± 0.00002	1.0004 ± 0.0004	-0.34
	JEFF-3.1	0.99519 ± 0.00002		-0.53
	JENDL-3.3	1.00193 ± 0.00002		0.14

Analysis Code	Neutron Cross Section Library	Calculated k_{eff} ± σ	Benchmark k_{eff} ± σ	$\frac{C-E}{E}(\%)$
MCNP5	ENDF/B-VII.0	0.98953 ± 0.00002	0.9928 ± 0.0028	-0.34
	JEFF-3.1	0.98772 ± 0.00002		-0.52
	JENDL-3.3	0.99401 ± 0.00002		0.11

Homogenization Uncertainty

~0.67% Δk_{eff} between JEFF-3.1 and JENDL-3.3

Calculated values are ~3.5 to 13.4 σ from *detailed* benchmark values

Results: 15 in. Annular Experiment

Detailed

Analysis Code	Neutron Cross Section Library	Calculated k_{eff} ± σ	Benchmark k_{eff} ± σ	$\frac{C-E}{E}(\%)$
MCNP5	ENDF/B-VII.0	0.99680 ± 0.00002	0.9993 ± 0.0003	-0.26
	JEFF-3.1	0.99451 ± 0.00002		-0.49
	JENDL-3.3	1.00125 ± 0.00002		0.19

~0.67% Δk_{eff} between JEFF-3.1 and JENDL-3.3

Simple

Analysis Code	Neutron Cross Section Library	Calculated k_{eff} ± σ	Benchmark k_{eff} ± σ	$\frac{C-E}{E}(\%)$
MCNP5	ENDF/B-VII.0	0.99257 ± 0.00002	0.9950 ± 0.0015	-0.26
	JEFF-3.1	0.99027 ± 0.00002		-0.49
	JENDL-3.3	0.99699 ± 0.00002		0.18

Calculated values are ~6.2 to 16.3 σ from *detailed* benchmark values

Homogenization Uncertainty

Neutron Spectral Data: Top-Reflected

Neutron Cross Section Library		ENDF/B-VII.0	JEFF-3.1	JENDL-3.3
k_{eff}		0.99804	0.99562	1.00202
$\pm\sigma_k$		0.00004	0.00004	0.00004
Neutron Leakage (%)		54.32	54.38	54.04
Fission Fraction, by Energy (%)	Thermal (<0.625 eV)	0.00	0.06	0.06
	Intermediate	7.48	7.66	7.35
	Fast (>100 keV)	92.51	92.28	92.59
Fission Fraction, by Isotope (%)	^{234}U	0.73	0.73	0.75
	^{235}U	98.29	98.27	98.26
	^{236}U	0.08	0.08	0.08
	^{238}U	0.90	0.91	0.91
Average Number of Neutrons Produced per Fission		2.592	2.590	2.597
Energy of Average Neutron Lethargy Causing Fission (MeV)		0.718	0.715	0.727

k_{eff} is sensitive to the neutron leakage

+0.1% net leakage ≈ -0.2% k_{eff}

Reflector Effects

- Compared reflected experiment to bare HEU configuration in previous benchmark
  - Mass difference
  - Most reactive portion of HEU discs replaced with Be for annuli
- Calculated reflector worth using MCNP5

Experiment	Mass Difference (kg)	Reflector Worth (ρ$)
Top-Reflected	9.922	10.7 ± 0.5
13” Annular	-13.497	8.5 ± 0.4
15” Annular	-3.258	4.2 ± 0.2

Conclusions

- Three beryllium-reflected experiments have been evaluated for inclusion in the ICSBEP Handbook
  - Annular experiments – HEU-MET-FAST-059
  - Top-reflected experiment – HEU-MET-FAST-069
  - To be included in September 2010 edition of handbook
- Small uncertainties
  - Significant differences between calculated and benchmark eigenvalues
  - More significant difference between calculations using different neutron cross section libraries

Acknowledgments

- Lee Montierth
  - Internal Review
  - Idaho National Laboratory
- John Mihalczo
  - Experimenter/Independent Review
  - Oak Ridge National Laboratory
- Fitz Trumble, Raymond Reed, Nathan Devine, and Nicholas Schira
  - Independent Review
  - Washington Safety Management Solutions
- Individuals and Countries Participating in ICSBEP

LEGO STAR WARS II
THE ORIGINAL TRILOGY
QUESTIONS?
LUCASARTS
WWW.LEGOSTARWARSII.COM

Detailed Benchmark Model: 15 in. Annulus

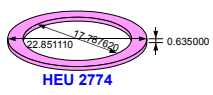
Top layer

17.770920 **0.5" Be** 1.270000

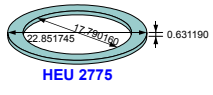
17.770920 **1.5" Be** 3.810000

Bottom layer

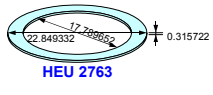
17.770920 **2.0" Be** 5.080000



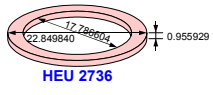
HEU 2774



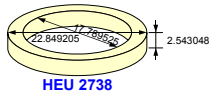
HEU 2775



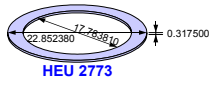
HEU 2763



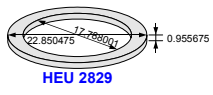
HEU 2736



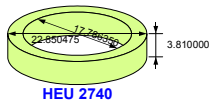
HEU 2738



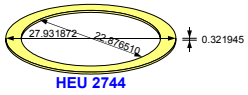
HEU 2773



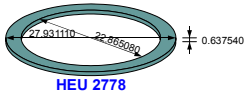
HEU 2829



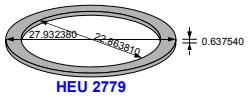
HEU 2740



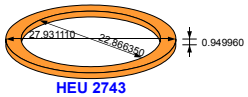
HEU 2744



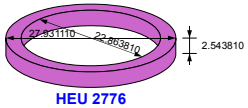
HEU 2778



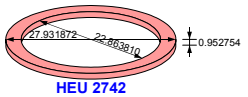
HEU 2779



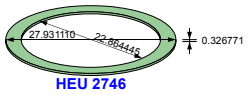
HEU 2743



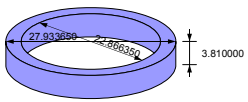
HEU 2776



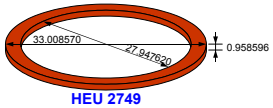
HEU 2742



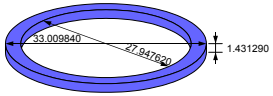
HEU 2746



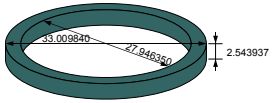
HEU 2748



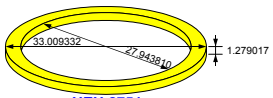
HEU 2749



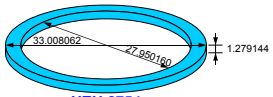
HEU 2755



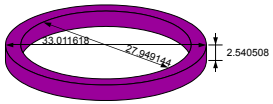
HEU 2757



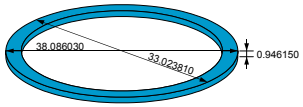
HEU 2751



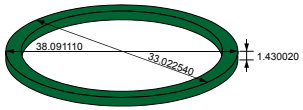
HEU 2754



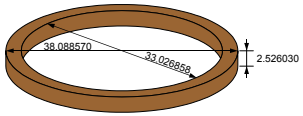
HEU 2756



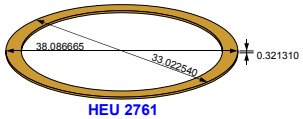
HEU 2784



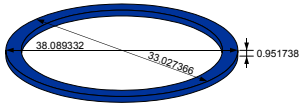
HEU 2766



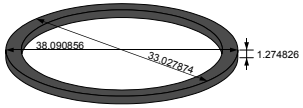
HEU 2739



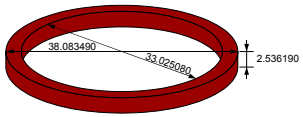
HEU 2761



HEU 2785



HEU 2848

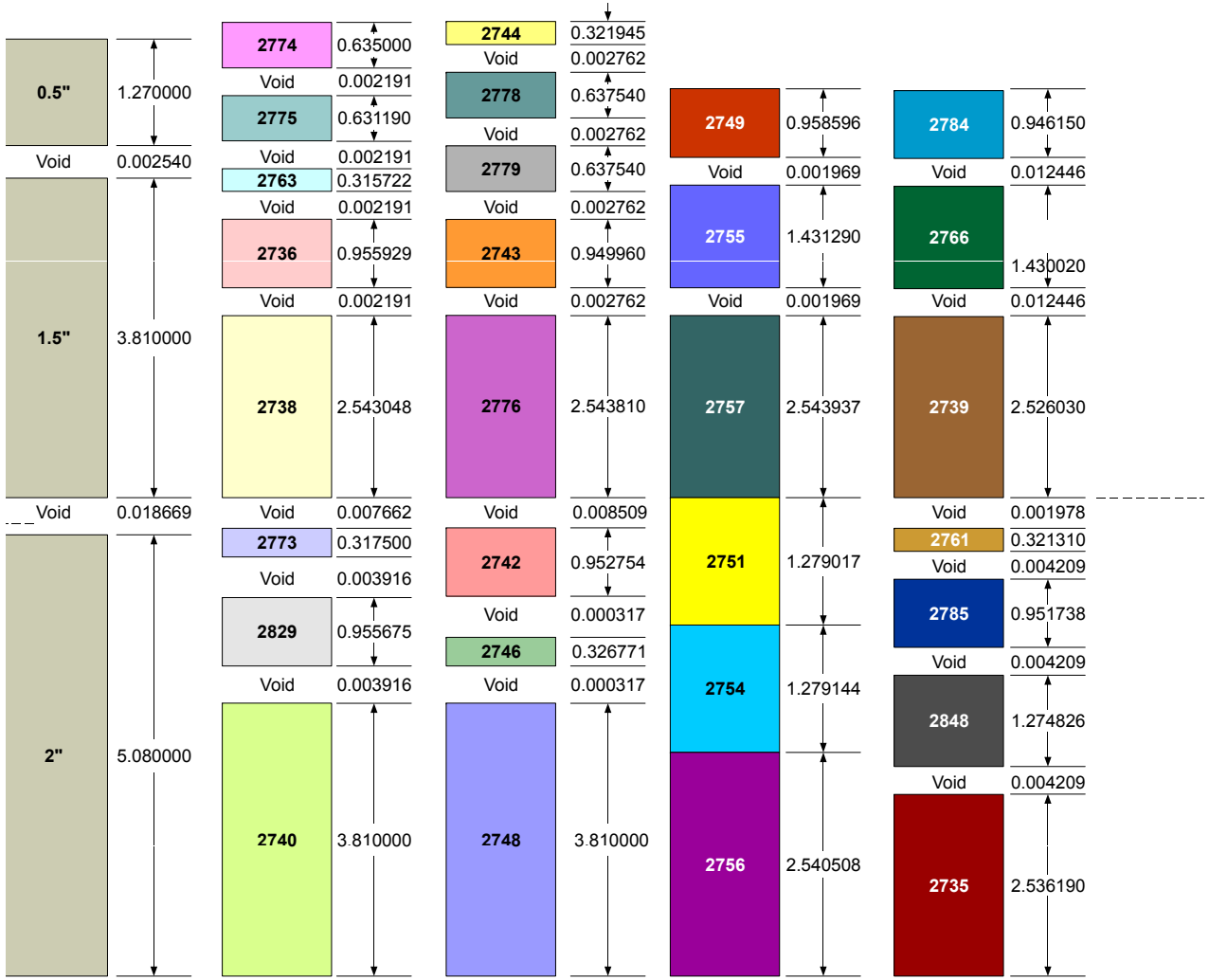


HEU 2735

Dimensions in cm

10-GA50002-53-3

Detailed Benchmark Model: 15 in. Annulus



Drawing not to scale
Dimensions in cm

10-GA50002-53-4